LOCATION OF THE ACCELERATION REGION OF THE BUNCHED ELECTRONS INFERRED FROM THE INTERACTION EVENT OF S–BURSTS WITH L–BURSTS AND N–BURSTS

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Abstract

Dynamic spectra of S–bursts of Jovian decametric radiations are obtained by using a high time resolution radio spectrograph with a time resolution of 2 ms and a bandwidth of 2 MHz. Within occurrence of 65 S–burst events observed in the period from 1983 to 1999, 26 events have been identified as the S–N burst events, which are characterized by the interaction between the S–burst emissions and the Narrow band emissions. In the dynamic spectra of the S–N burst, the trend of emissions with negative and slower frequency drift named as "Trailing Edge Emission" are often observed shortly after the appearance of the S–burst. Detailed analyses of these phenomena revealed that the Trailing Edge Emission is not a manifestation of S–burst with slower drift rate but a variation of N–burst. The results suggested that S–burst and the associated Trailing Edge Emission are formed simultaneously started from a common region with different drift rates. It has further been suggested that the appearance of the S–bursts is not controlled by the geometrical effect between the source region and the observer, but directly reflects the generation of the source region widely distributed in an altitude range from a few thousands km to 30.000 km, along the Io flux tube.

1 Introduction

The S–bursts of the Jovian Decametric Radiation belong to a category of the shortest time duration phenomena, which shows the rapid negative frequency drift during a few tens of milliseconds with the frequency drift rate (df/dt) of a few tens of MHz/s. In several proposed models, it has been widely accepted that an upward stream of bunched electron clouds generate the S–bursts approximately at the local electron gyrofrequency. The fundamental problem is the origin of these bunched electrons. Two possible locations

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of the acceleration region of the bunched electrons have been proposed, i.e. one near Io and the other near the surface of Jupiter. Ellis [1975] has pointed out that the drift rates of S–bursts are generally increasing with increasing the frequency from 8 to 24 MHz. He has proposed a model of the formation of bunched electrons which are originally accelerated at Io. The bunched electrons are making bounce motions between the mirror points keeping the first adiabatic invariant constant [Ellis, 1975]. The drift rates of S–bursts in a high frequency range over 24 MHz have further been studied by Desch et al. [1978], Riihimaa [1979], Flagg and Desch [1979], and Ellis [1982]. Their results unanimously showed that the drift rate of the S–burst increases with increasing the frequency even in a high frequency range. Their results are, then, contradictory to the model proposed by Ellis [1975], since the trapped electrons accelerated at Io are supposed to decrease the drift rates of the S–bursts in the high frequency range because of the mirror motion of electrons. Leblanc et al. [1980] has proposed another model of the acceleration of bunched electrons; the electrons are accelerated near the Jovian ionosphere along the field line with a direction of outward. The existence of such electrons can explain the observed trend of the drift rate of S–bursts [Leblanc et al., 1980]. However, Zarka et al. [1996] have recently reported on the basis of their high frequency range observations over 32 MHz, that the dependence of drift rates on the frequency is different from previous results. Zarka et al. [1996] showed that the drift rate in the high frequency range rapidly decreases with the increment of the frequency. Then, their result supports the Ellis's model of trapped electrons which are accelerated at Io. These different observational results can be attributed to, the difficulty in the precise measurements of the drift rates due to the scarcity of S–burst occurrence in this high frequency range. Therefore, it is still unknown where the electrons are accelerated. In this paper we studied the origin of the S–bursts from the analysis of the interaction between S–bursts and N–bursts which have a restricted frequency range showing an almost constant frequency and a narrow bandwidth. The generation process of N–bursts is still unknown, too. In the case of the emissions in the Io–B source, an S–burst occasionally makes an interaction with the N–burst. We call this interaction phenomenon between the S–burst and the N–burst as "S–N burst event". In the dynamic spectra of S–N bursts, an S–burst appears as sloping line crossing a N–burst. At cross over point, there is a gap of N–burst emission with a substantial fraction of a second. Shortly after the appearance of the S–burst, the second trend of the negative frequency drift is generated with slower drift rate; this new trend has been called "Trailing Edge Emission" [Riihimaa and Carr, 1981]. In the present report, we study the characteristics of the S–N burst event by using high–resolution spectra with the bandwidth of 2 MHz. From the characteristics of the S–N burst, we can obtain an important clue to seek for the possible generation mechanism of the S–bursts.

2 Characteristics of Trailing Edge Emission

As shown in Figure 1(a), an S–N burst has complex feature adding a new type emissions named "Trailing Edge Emission(TEE)" (see Figure 1(b)) showing an interaction of S–bursts with N–bursts in the dynamic spectra. In the previous works, the TEE was recognized as a kind of S–bursts because it has a similar falling tone spectra [Riihimaa and Carr, 1981]. However, since the occurrence probability of TEEs is very small compared

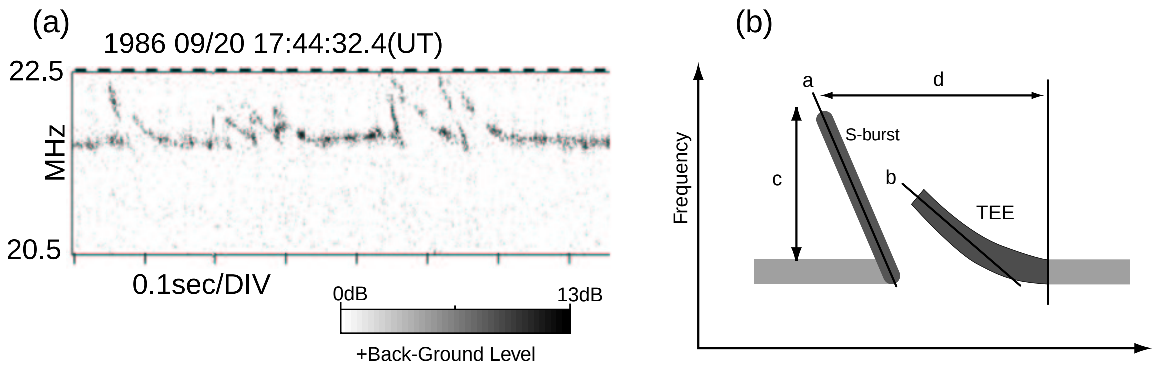

Figure 1: (a): A typical example of S–N burst. (b) Definition of parameters. a: S–burst Drift Rate. b: Trailing Edge Drift rate. c: S–burst frequency range. d: Duration time.

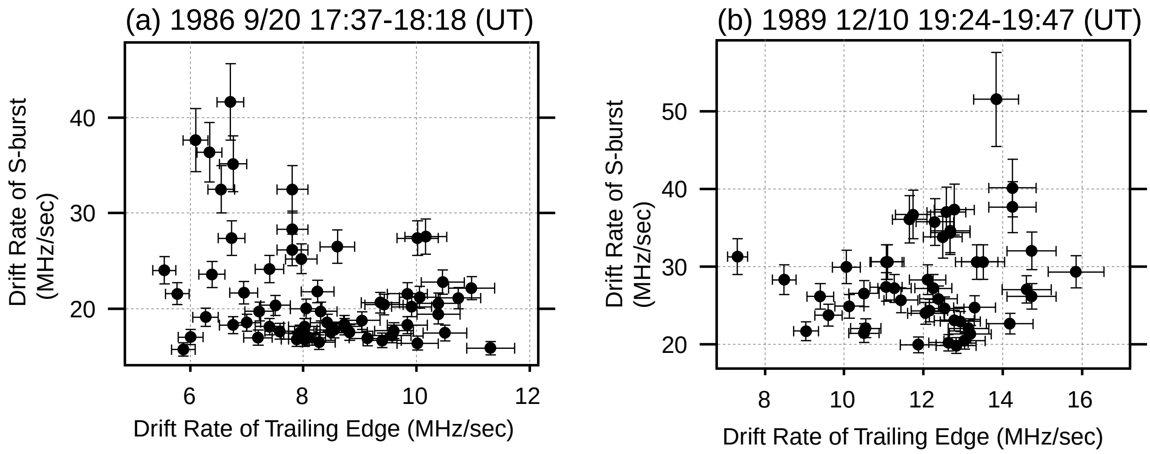

Figure 2: Diagrams which show the relation between the drift rates of S–burst and TEE.

with other DAM emissions and it can only be observed by using the high–time–resolution dynamic spectrograph, the detailed characteristics of TEEs have not been well understood yet. Therefore, it has been still unsolved problem whether the TEEs belong to a category of S–bursts as suggested by Riihimaa and Carr [1981] or not. In this section, we analyzed the basic characteristics of the TEEs to identify the nature of the TEE.

2.1 Relations between S–burst and TEE

The TEE is characterized by a nature of falling tone forming S–burst–like dynamic spectra. However, it is clearly shows that the drift rates of the TEEs are lower than those of the S–bursts. The correlation of drift rates between the pair of S–burst and TEE for each S–N burst events is interesting. In Figure 2, drift rates of the S–bursts are plotted versus those of associated TEEs for two events. The uncertainties of individual measurements are

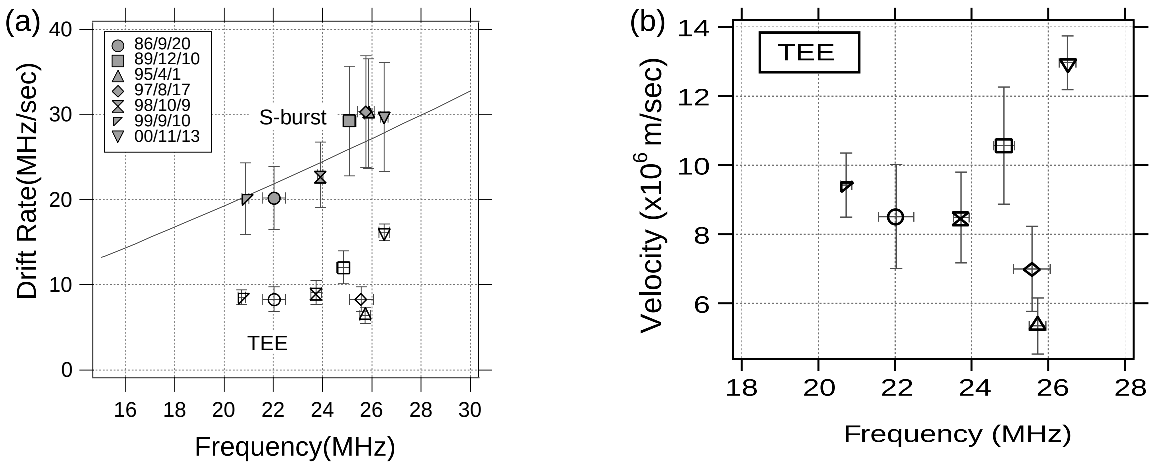

Figure 3: (a): The frequency dependences of drift rates of S–bursts and TEE. The solid curves are calculated with $V_{//}$=0.08 c. (b): The frequency dependences of the averaged velocities of TEEs.

indicated by error bars in the figures. As can be seen in Figure 2, there is no remarkable correlation between the drift rate of S–burst and that of the associated TEE. Further, the frequency dependence of the drift rates of S–bursts and the associated TEEs in the S–N events are indicated in Figure 3(a) for 7 S–N burst events, where the average drift rates of S–bursts and TEEs (indicated by solid and open marks) are plotted as a function of the observation frequency. Associated horizontal and vertical bars indicate the ranges of the deviation of the drift rates and the frequencies around their average values for each events. As mentioned in the introduction, the drift rate of S–burst depends on the observed frequency. The drift rate tends to increase with frequency, although the dependence in the high frequency range above 30 MHz is not clear. As can be seen in Figure 3(a), the drift rate of the S–burst measured in the S–N burst events has the same frequency dependence as a simple S–burst events. On the other hand, there is no clear dependence in the drift rates of TEEs. The velocity of the generation region along the magnetic field line has been estimated as a function of the frequency for both S–bursts and TEEs. Averaged velocities of generation region of S–bursts show relatively small variance around the constant value of 24×10^6 m/s (0.08 c) (see Figure 3(a)), while TEEs show different tendency as indicated in Figure 3(b) where averaged velocities of TEEs show variety depending on the frequency of each event. It is noted that the flow velocity of generation region of TEE varies largely from one event to another.

2.2 Relations between TEE and N–burst

Figure 4 shows an example of S–N burst which was observed with high time resolution of 2 ms to examine the combinations of S–burst, TEE and N–burst in detail. The thick and thin bars marked on the top of this panel indicates the polarization status of RH and LH switched alternatively. In the panel (b), temporal variations of the center frequency

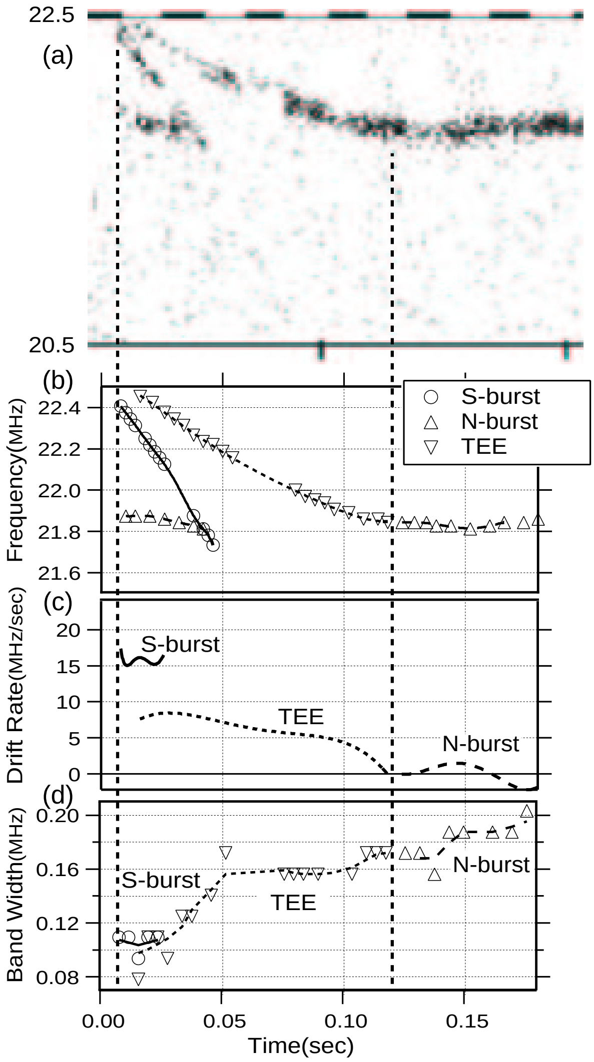

Figure 4: Properties of the microstructures of S–N burst.

of the emissions are indicated by open circles, triangles, and inverse triangles for the S–burst, the N–burst, and the TEE, respectively. Curves in this figure indicates trends of these bursts by using polynomial functions. The temporal variations of drift rate and bandwidth of the emissions are also indicated in the panel (c) and (d), where drift rates are calculated from the fitted curves shown in panel (b). As can be seen in the panel (c), the drift rate of the TEE decreases gradually, and finally, merges into the trend of N–burst. The drift rate of S–burst, on the other hand, keeps almost a constant value. In the panel (d), it is shown that the bandwidths of S–burst and N–burst keep almost constant values, while the bandwidth of the TEE rapidly increases during the first 0.05 s and then gradually increases; and finally, the bandwidth of TEE becomes almost the same as that of N–burst at the merging point. At this merging point, the center frequency, bandwidth, and drift rate of the TEE is smoothly connected to those of the N–burst. Figure 4 shows

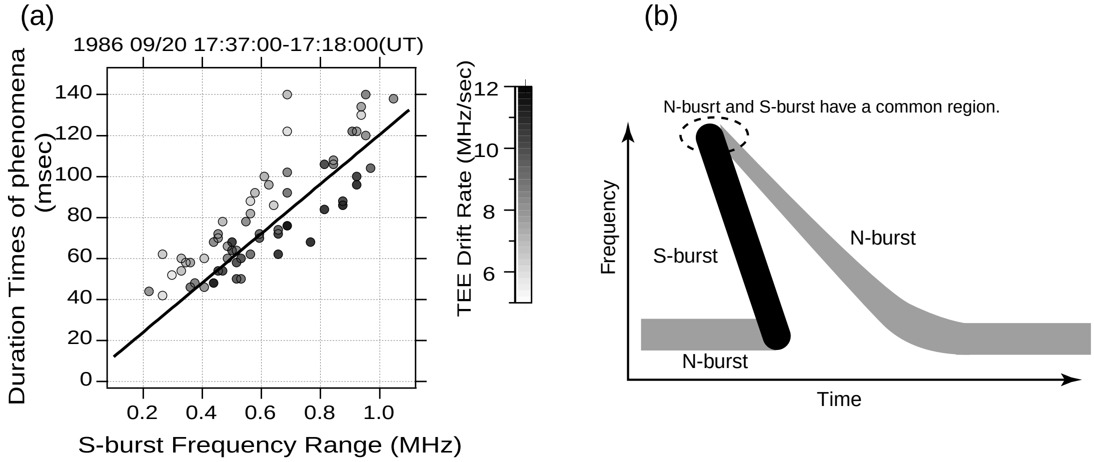

Figure 5: (a): The "duration times" are plotted as a function of the "S–burst frequency range". (b) An illustration of the structure of S–N burst.

an example, however, the same results can be found generally in the dynamic spectra of the S–N burst. A significant point in the result of the present analysis is that the trend of the TEE is connected to the N–burst smoothly at the merging point. This evidence seems to be contradictory to the argument of Riihimaa and Carr [1981] who proposed that the TEE is another trend of the S–burst which has a different frequency drift rate. If the TEE essentially posses a nature of the S–burst as suggested by Riihimaa and Carr [1981], it is difficult to explain the characteristics of the TEE at the merging point with N–burst. On the basis of the present study on the behavior of TEEs and N–bursts, it can be suggested that the TEE phenomenon does not belong to the category of the S–bursts, but to the category of the N–bursts.

3 Origin of Trailing Edge

The result of the present data analysis of S–N burst shows that TEEs do not belong to the S–burst, but shows property of N–burst. On the other hand, since the TEEs appear only in the cases of S–N burst events, the generation process of the TEE should be related to a mechanism of the S–burst. To identify the origin of TEEs, we have investigated various parameters to characterize the TEEs in the dynamic spectra. Considering these evidences, it can be suggested that the TEE is triggered by the formation of electron cloud moving upward from the Jovian ionosphere generating the S–bursts. Further information on the relation between the S–bursts and the TEEs is obtained from the "duration time" ("d" in Figure 1(b)). The drift rates of the TEEs are also indicated by the gray scale for each S–N burst events. It is obvious that there is definite positive correlation between these two parameters. A linear solid line superimposed on the data indicate a relation estimated from the assumption that both TEEs and S–bursts are started from a common origin after the formation of their generation regions. The fact implies that both TEEs

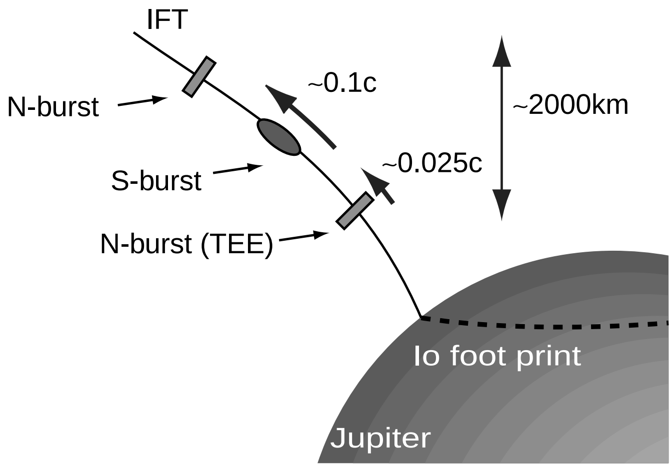

Figure 6: The relation of positions of source regions along a magnetic field line.

and S–bursts are started from a common origin, which also suggests that the generation regions of the TEEs and the associated S–bursts are both created simultaneously in the Io flux tube through an interaction process. The generation region of the TEEs, however, does not radiate electromagnetic waves at the beginning of formation. Electromagnetic emissions are generated in a few tens of milliseconds after the formation of TEE region.

4 Discussions and conclusions

The statistic analyses of the present study indicate that there is no correlation between the drift rates of two trends of emissions which are identified as S–burst and TEE. The important thing pointed out in this paper is that TEE is more likely to be a part of the N–burst having a slow negative frequency drift. Furthermore, TEEs and S–bursts are shown to be originated in a common region. A significant point revealed from the present study is that the properties of the TEEs are essentially identical with the N–burst for their center frequency, bandwidth and the drift rate which are continuously connected from the TEE to the N–burst at the merging point. In this case, the frequency drift rate of the TEE is quite independent from that of the S–burst. On the basis of these evidences, we can state that the TEE phenomena are not in the category of S–bursts but belong to the category of N–burst.

The observed frequency range shows that S–burst is restricted within a few MHz frequency range that corresponds a few thousands km of distance for the traveling electrons along the magnetic field line. A possible model was proposed by Ellis [1982] and Zarka [1998] to explain the limited frequency range observed for the S–bursts. To explain the observational facts, a thin emission cone is required sweeping the direction of the observer. They estimated the thickness of the emission cone to be about 0.5° [Ellis, 1982] or about 2° [Zarka, 1998]. Our present observation results, however, can not support their interpretations. Considering the evidence that the apparitions of S–burst and N–burst occur at the same time and at the same frequency, it is not likely to state that the occurrence of the S–bursts is controlled by such a geometrical effects. As a consequence of this study, the apparition of S–burst in the dynamic spectra, then, does not reflect the geometrical relation between the source and the observer, but corresponds to the formation of electrons' cloud and the generation of electromagnetic waves. Furthermore, based on the point that the S–burst and the associated TEE have a common origin, the generation of the S–burst can not be considered separately from the existence of the associated TEE.

Therefore, we suggest that the acceleration mechanism of bunched electrons that are responsible for the generation of the S–bursts is intimately related to the formation process of the electrons which generate the N–bursts. The observed frequency of the S–bursts from 5 MHz to 38 MHz corresponds to the altitude range of the source positions from a few thousands km to 30.000 km assuming that the radiations take place at the local electron cyclotron frequencies. The acceleration region of the bunched electrons are thought to be distributed in this altitude range along the Io flux tube. The frequency range of each emission is a few MHz, so that the spatial extent of the source region is a few thousands km. The parallel velocities of bunched electrons with a speed in a ranges from 0.06 c (0.9 keV) (c is the light velocity) to 0.13 c (4.1 keV) give a good agreement with the observed frequency drift rates. Summarizing the results of the present study, the region of N–bursts locates and persists for an entire period of the event except for the intermittent moment of the S–burst encounter. As shown in Figure 6, at the start time of TEE phenomena, a new region of N–burst is generated moving upward, at the same time, the formation of bunched electrons takes place that moves with a high speed of about 0.1 c. Then, the high speed bunched electrons merge with the region of the N–burst in the highest altitude; this entry of the bunched electrons into the N–burst region causes the disappearance of the N–burst. Meanwhile, the new N–burst region of TEE moves up gradually, until it reaches the level of the original source region of the N–burst.

The physical process of the source region of N–burst is not understood yet. Flagg et al. [1976] supposed a generation mechanism of the N–burst as the coherent cyclotron mechanism, however, they have not clarified in detail. In the present study, it has been shown that the formation of a new N–burst source region takes place creating a TEE in lower altitude ionosphere where S–burst electrons are most likely to be formed. Therefore, it may be suggested that the generation region of the N–burst contains the parallel electric field which accelerates the bunched electrons for the S–burst.

In the present study we may not go into a detailed point about the formation of the parallel electric field but observations show that the localized parallel electric fields apparently appear along the magnetic field line in the S–N burst event. In the S–N burst events, two kinds of potential drops seem to appear in the Io flux tube. One potential drop is created first at a high altitude which forms the generation region of the quasi steady N–burst. And then, at lower altitude, the other potential drop appears suddenly, and the bunched electrons for the S–burst is accelerated by this electric field. Because the bandwidth of the TEE is narrower than 100 kHz, the spatial extent of the acceleration region of S–burst electrons along the magnetic field line is very thin, with a width less than 100 km.

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